The Effect of Process Parameters on Mechanical Stir Casting Process

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***Abstract*— In this study, composites-casting with an aluminium alloy C355 and 5(wt.%) of SiC reinforcement were made. Side by side investigations of tensile strength of the composite was done, 17 samples were fabricated for this study and these samples were machined as per dimension by which tensile test samples were obtained. Aluminium has low weight since its mechanical properties are not so good as compared to iron (Fe). So by reinforcing a material like SiC, mechanical properties can be improved of Al and it can be used in military and aerospace industry because of its low weight and good mechanical properties which is the primary requirement for aerospace industry. The mechanical properties of the fabricated composite are improved in relation to the base alloy, which have an enhanced wear resistance, favourable mechanical properties at room temperature.**

***Keywords*— MMC; RSM; Box Behnken Design; ANOVA; Tensile strength**

I. INTRODUCTION

Metal matrix composite have potential application in many fields because of their good physical and mechanical properties, such as high specific strength and stiffness, SiC particles. Reinforced Aluminium matrix composite can be fabricated with the stir casting process, which is one of the chief developments in fabricating Al-355/SiC composite.

The 355 type alloy, especially C-355, is one of a small group of select alloys used to make military and aerospace parts that meet the MIL-A-21180 specification for "Premium strength/Quality" casting (the 206 alloys are also in this group, as are Al-356 and Al-357).They are used in aircraft crank cases, gearboxes, housings and supports, as well as in impellers for superchargers. This alloy has already been used for semi solid processing and to a limited extent for squeeze casting as well. Silicon carbide (SiC), also known as carborundum, is a compound of Silicon and Carbon with chemical formula SiC. It occurs in nature as the extremely rare mineral moissa-nite. Grains of SiC can be bonded together by sintering to form very hard ceramics which are widely used in application requiring for endurance, such as car brakes, car clutches and ceramics plate in bullet proof vests.Stir casting is a method of casting process in which materials are mixed by stirring rotation to form vortex and then prepared molten material poured into the mould for solidification [1-2].

II. LITERATURE REVIEW

Han Jian-min et al described that a stir casting method is one of the most competitive methods for fabricating SiC particle reinforced Aluminium matrix composites because of its low cost with cost with competitive quality [1]. Z.MISKOVIC et al explained composites-casting with Aluminium A356 alloy base and additions of 1, 2 and 3 % (wt.) of Al2O3 reinforcements of 12 micrometer size were made [2]. Shuewian H.Juang et al preformed A356 alloy with thixotropic structure (designed SSM-A356) was systematically studied on mechanical properties in order to establish the database for further investigations in forming and heat treatment [3]. METIN KOK studied the machinability 2024Al/Al203 particle composite was investigated in terms of tool wear, tool life and surface roughness by turning specimens withTiN(K10) coated and HX uncoated carbide tools in different cutting conditions [4]. Jashmi Hasim described that in a normal practice of stir casting technique, cast metal matrix composites (MMC) is produced by melting the matrix material in a vessel, and then the molten metal is stirred thoroughly to form a vortex and the reinforcement particles are introduced through the side of the vortex formed. From some point of view this approach has dis-advantages, mainly arising from the particle addition there is undoubtedly local solidification of the melt induced by the particles, and this increase the viscosity of the slurry [4]. Amir Parkel et al found out the effect of extrusion ratio on the microstructure, mechanical properties, and fracture behavior of metal-matrix composite (MMCs) of AA6061 alloy reinforced with 10 volume percent particulate SiC with an average size of 46 micrometer was studied. Graham Withers described that Aluminium composites with excellent mechanical and physical properties can be produced at low cost by reinforcing the Aluminium matrix with spherical ceramic particles derived from fly ash. Chennakesava Reddy et al describes that the material selection criteria involve the requirement of high strength and good corrosion resistance Aluminium alloys for the matrix materials [5].

III. METHODOLOGY

Response surface methodology (RSM) is a collection of mathematical and statistical techniques for empirical model building. By careful design of experiments, the objective is to optimize a response (output variable) which is influenced by several independent variables (input variables). An experiment is a series of tests, called runs, in which changes are made in the input variables in order to identify the reasons for changes in the output response. Originally, RSM was developed to model experimental responses (Box and Draper, 1987), and then migrated into the modeling of numerical experiments.

The difference is in the type of error generated by the response. In physical experiments, inaccuracy can be due, for example, to measurement errors while, in computer experiments, numerical noise is a result of incomplete convergence of iterative processes, round-off errors or the discrete representation of continuous physical phenomena. The application of RSM to design optimization is aimed at reducing the cost of expensive analysis methods (e.g. finite element method or CFD analysis) and their associated numerical noise. The problem can be approximated as described in with smooth functions that improve the convergence of the optimization process because they reduce the effects of noise and they allow for the use of derivative-based algorithms. Venter et al. (1996) have discussed the advantages of using RSM for design optimization applications.

An easy way to estimate a first-degree polynomial model is to use a factorial experiment or a fractional factorial design. This is sufficient to determine which explanatory variables have an impact on the response variable (s) of interest. Once it is suspected that only significant explanatory variables are left, and then a more complicated design, such as a central composite design can be implemented to estimate a second-degree polynomial model, which is still only an approximation at best. However, the second-degree model can be used to optimize (maximize, minimize, or attain a specific target for) a response.

For example, in the case of the optimization of the calcinations of roman cement, the engineer wants to find the levels of temperature($x1$) and time ($x2$) that maximize the early age strength (y) of the cement. The early age strength is a function of the levels of temperature and time, as follows:

$$y = f(x1, x2) + e \tag{1}$$

Where 'e' represents the noise or error observed in the response y. The surface represented by $f(x1, x2)$ is called a response surface.

The Box-Behnken design is an independent quadratic design in that it does not contain an embedded factorial or fractional factorial design. In this design the treatment combinations are at the midpoints of edges of the process space and at the center. These designs are rotatable (or near rotatable) and require 3 levels of each factor. The designs have limited capability for orthogonal blocking compared to the central composite designs [6].

IV. EXPERIMENTATION

A. Material selection

1) Matrix Alloy: In this study, the alloy C-355 is used, which is widely used Aluminium casting alloy. It has a very good mechanical strength, ductility, hardness, fatigue strength, pressure tightness, fluidity and machinability. This alloy is used in many industrial applications such as airframe casting, machine parts, truck chassis parts, aircrafts and missile components and structural parts requiring high strength.

2) Reinforcement Material: Silicon carbide is used as the reinforcement phase. To select a suitable reinforcement material for Aluminium, important facts such as density, wettability and thermal stability were considered. Silicon carbide is a widely used reinforcement material because of its good wettability with the Aluminium matrix. However, SiC reacts with molten Aluminium at temperatures above 1000 K to form $Al2O3$, releasing Silicon into the matrix. Nevertheless, this reaction can be suppressed by high Si content.

B. Experimental Procedure

Aluminium alloy C355 heated to above its liquid temperature in muffle furnace. The temperature was recorded using chromel-alumel thermocouple which was 700°C to 790°C. The C355 Aluminium alloy was firstly melted in furnace, refined and the temperature was maintained as per required temperature. SiC particle with

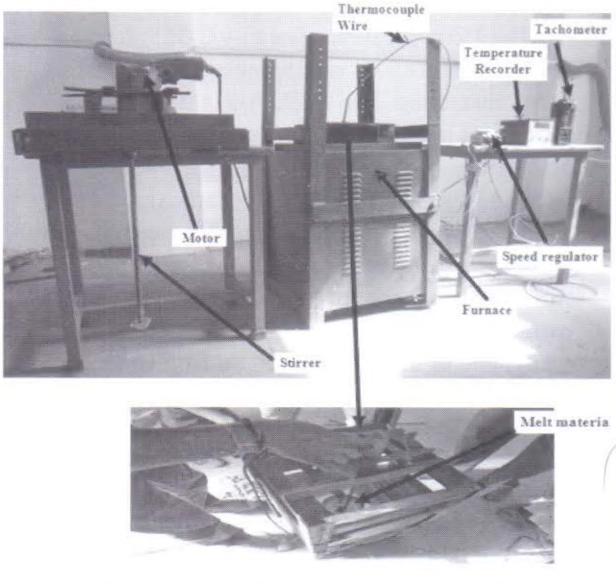

Fig. 1 Experimental setup of mechanical stir casting

an average size of 50 micrometer were chosen. The 5% SiC reinforcing particles were added on the surface of the molten liquid before preheating. The SiC particle disperses into the melt material. C355+5%SiC MMC stirred about 200 to 600 seconds and the stirring speed of melt material was 140 to 240 rpm. The speed of motor was regulated by using a speed regulator. The speed was recorded by using a non-contact tachometer.

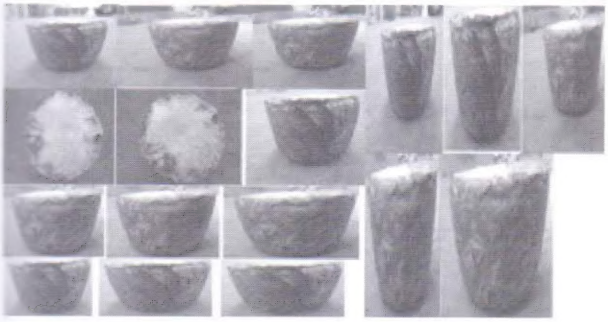

Fig. 2 Produced 17 pieces of Metal Matrix Composites (C355+5%SiC)

On the basis of pilot test run, following process parameters ranges are decided which was shown in Table 1.

TABLE I
PROCESS PARAMETERS WITH THEIR RANGES

S.No.	Parameters	Value set as
01	Temperature	700-790 °C
02	Time	200-600 seconds
03	Speed	140-240 rpm

C. Tensile Test

For tensile testing of Al alloy C355/5 %(wt.) SiC compo-site material, 17 samples have been prepared as per specification.

TABLE II
DESIGN MATRIX AND EXPERIMENTAL RESULTS FOR TENSILE STRENGTH

S.No.	Stirring temp. (°C)	Stirring Speed (rpm)	Stirring time (seconds)	Tensile Strength (MPa)
1	790	240	400	380
2	700	140	400	370
3	700	190	600	420
4	745	140	200	220
5	790	190	200	210
6	745	240	600	420
7	790	190	600	330
8	745	140	600	310
9	745	190	400	320
10	745	190	400	315
11	790	140	400	279
12	700	240	400	470
13	745	190	400	329
14	745	240	200	250
15	745	190	400	327
16	745	190	400	325
17	700	190	200	300

Fig.3 Tensile Specimens

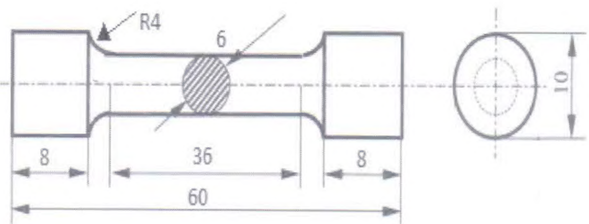

Fig. 4 Specification and dimension of

V. RESULT AND DISCUSSION

The mechanical stir casting is seen to be the cheapest method of producing MMC compared to other methods such as powder metallurgy and simple stirring process. However the main MMC fabrication problems such as wettability between substances, the chemical reaction between them, the distribution of the reinforcement particles in the matrix and also the porosity content in the matrix still remain and research continues aiming to solve them. In normal stir casting technique, cast MMC is produced by melting the matrix materials then the molten metal is stirred thoroughly to form a vortex and the rein-forcement particles are introduced through the side of the vortex formed. Research related to this type of cast MMC producing method is broad and still going on. However the main approach used remains the same as mentioned above. From other point of view, this approach of producing MMC by stir casting has disadvantages, mainly rising from the particle addition and the stirring method. Particles will induce local solidification to the molten matrix and this increase the viscosity of the slurry. A top addition method and the vortex formation will introduce air into the slurry. The rates of particle also need to be showed down, especially when the volume fraction of the particle also need to be slowed down, especially when the volume fraction of the particle to be used increase.

A. Tensile Strength

Tensile strength measures the force required to pull something such as rope, wire, or a structural beam to the point where it breaks. The tensile strength of a material is the maximum amount of tensile stress that it can take before failure, for example breaking.

TABLE III
ANOVA TABLE FOR TENSILE STRENGTH

Source	Sum of square	DF	Mean square	F Value	p-value Prob>F
Model	76344.89	9	8482.77	92.20	<0.0001
A-Temperature	16290.12	1	16290.12	177.05	<0.0001
B-Speed	14535.13	1	14535.13	157.98	<0.0001
C-Time	31250.00	1	31250.00	339.65	<0.0001
AB	0.25	1	0.25	2.717E-003	0.9599
AC	0.000	1	0.000	0.000	1.0000
BC	1600.00	1	1600.00	17.39	0.0042
A2	4662.00	1	4662.00	50.67	0.0002
B2	1406.21	1	1406.21	15.28	0.0058
C2	7242.84	1	7242.84	78.72	<0.0001
Residual	644.05	7	92.01		
Lack of fit	515.25	3	171.75	5.33	0.0698
Pure error	128.80	4	32.20		
Cor Total	76988.94	16			
Std. Dev.	9.59	R-Squared			0.9916
Mean	327.94	Adj R-Squared			0.9809
C.V.%	2.92	Pred R-Squared			0.8903
PRESS	8445.25	AdeqPrecision			34.645

1) Final Equation in Terms of Coded Factors:

Tensile strength= +323.20-45.13 * A+42.63 * B+62.50 * C+0.25 * A * B+ 0.000 *A* C +20.00 * B * + 33.27 * A2 +18.27 * B2-41.47 * C2 (2)

2) Final Equation in Terms of Actual Factors:

Tensile Strength=+10169.2388-2.80808 * Speed + 0.76200 * Time+1.11111 E-004 * Temperature * Speed +8.36861 E-017 * Temperature * Time + 2.00000 E-003 * Speed * Time + 0.016432 * Temperature2 + 7.31000 E -003 * Speed2-1.03687 E-003 * Time2• (3)

3) Predicted V/S Actual: Each observed value is compared with the predicted value calculated from the model in figure 5. It can be seen that the regression model is fairly well fitted with the observed values.

4) Normal Plot of Residuals: Figure 6 displays the normal probability plot of the residuals for tensile strength. Notice that the residuals are falling on a straight line, which means that the errors are normally distributed.

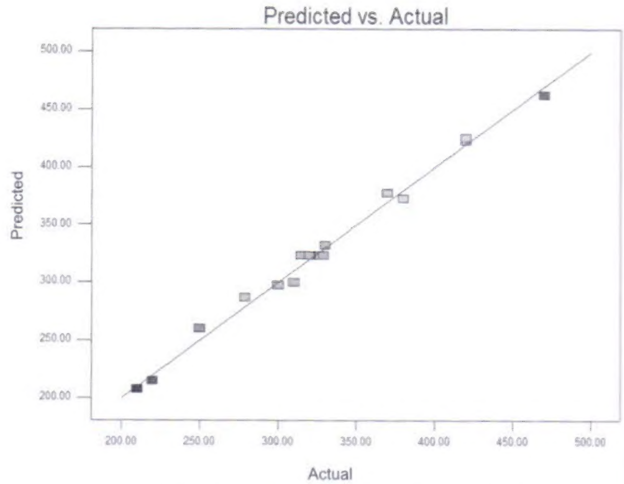

Fig. 5 Relation between predicted Vs actual value

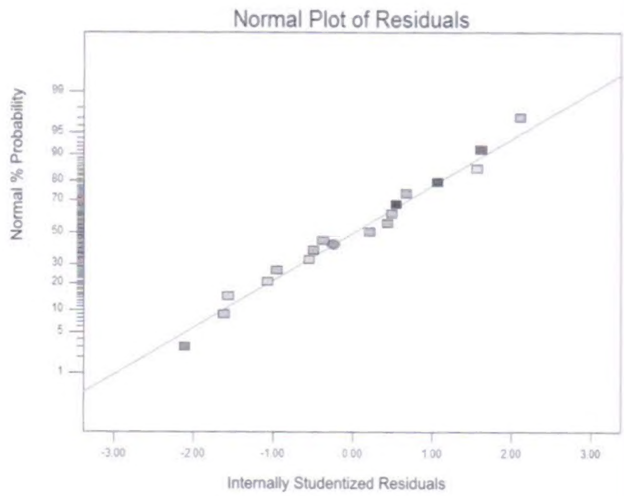

Fig 6 Relation between normal % probability and Residuals

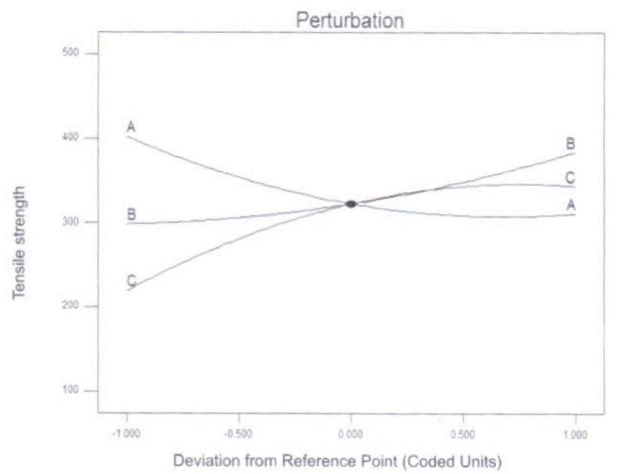

Fig 7 Relation between tensile strength and deviation value

5) Interrelation between Stirring Time, Temperature and Speed: For better result stirring time, temperature and speed should intersect to each other as shown in figure 7. If these three parameters do not intersect each other at any point then the tensile strength will be low.

B. The effect of process parameters on tensile strength

1) Effect of stirring temperature on tensile strength: It can be seen from figure no.8 that by increasing the temperature, tensile strength decreased because when stirring is done at higher temperature it takes much time to get solidified, due to which all the SiC particles go down to bottom of crucible. And when MMC composite solidified, SiC particles in C355 Matrix not distributed so well. So by increasing the stirring temperature, tensile strength decreases.

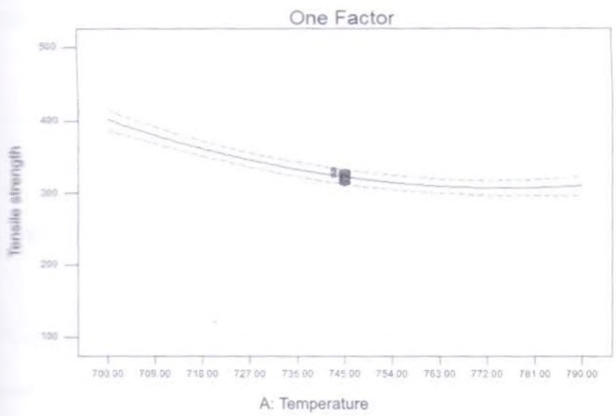

Fig. 8 Relation between Temperature and Tensile Strength

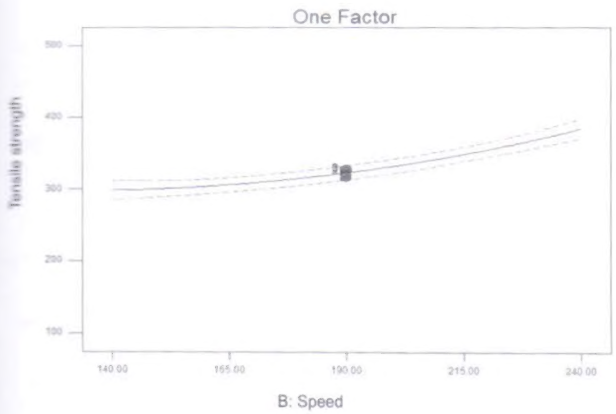

Fig. 9 Relation between Speed and Tensile Strength

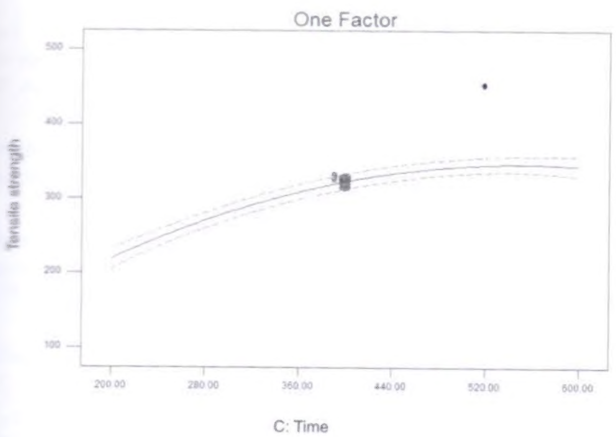

Fig. 10 Relation between Stirring Time and Tensile Strength

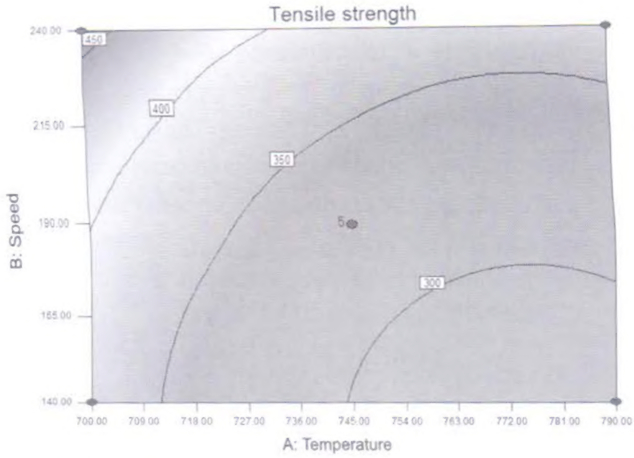

Fig. 11 Relation between speed, temperature and tensile strength

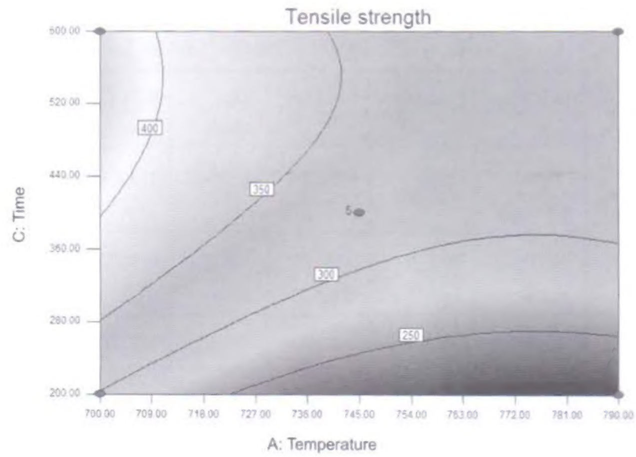

Fig. 12 Relation between time, temperature and tensile strength

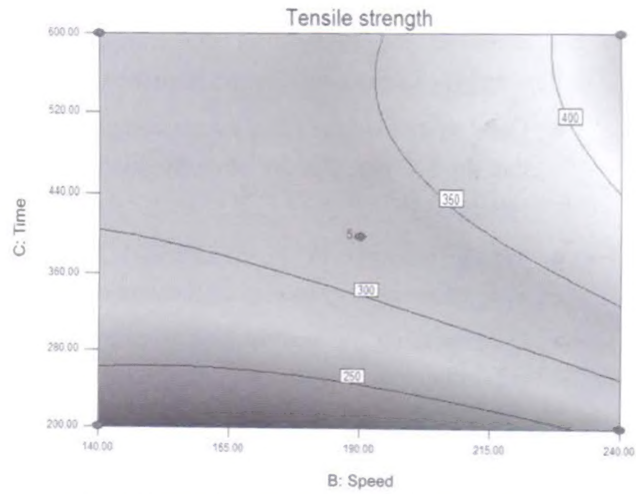

Fig. 13 Relation between time, speed and tensile strength

2) Effect of stirring speed on tensile strength: When speed increases tensile strength also increased because the mixing of reinforcement material will be good due to high speed. The tensile strength is high because of good mixing of both materials. So always a high speed is desirable for better results.

3) Effect of stirring time on tensile strength: When stirring time increases tensile strength also increased because the mixing of reinforcement material will be good due to more time of mixing. The tensile strength is high because of good mixing of both materials. So always a more stirring time is desirable for better results, shown in figure 10.

C. Result (Point prediction)

TABLE IV POINT PREDICTION

Factor	Name	Level	Low level	High level	Std. Dev.	Coding
A	Temperature	745.00	700.00	790.00	0.000	Actual
B	Speed	190.00	140.00	240.00	0.000	Actual
C	Time	400.00	200.00	200.00	0.000	Actual

Response	Prediction	Std.Dev	SE Mean	95% CI Low	95% CI High
Tensile Strength	323.2	9.59204	4.28969	313.056	333.344
SE Pred	95% PI Low	95% PI High	95% TI Low	95% TI High	
10.5075	298.354	348.046	270.67	375.73	

VI. CONCLUSIONS

A mechanical stir casting process was successfully utilized for casting (C355+5%SiC) matrix composites. The distribution of SiC particles surrounding C355 phase has improved the strength of the composites. The following conclusions can be drawn from the analysis;

- Good strength of the metal matrix composite shows that the SiC particles are properly distributed with matrix C355.
- Tensile strength of (C355+5%SiC) Aluminium alloys decreases, by increasing the temperature.
- By increasing the stirring time from minimum to maximum limit, the tensile strength increases.
- Tensile strength increases while stirring speed increases.
- An empirical relationship was developed to predict the tensile strength incorporating mechanical stir casting process parameters at 95% confidence level. The predicted value for tensile strength was found 323.2 MPa. At the 95% PI low value was found 298.354 MPa while at 95% PI high value was found 348.046 MPa.

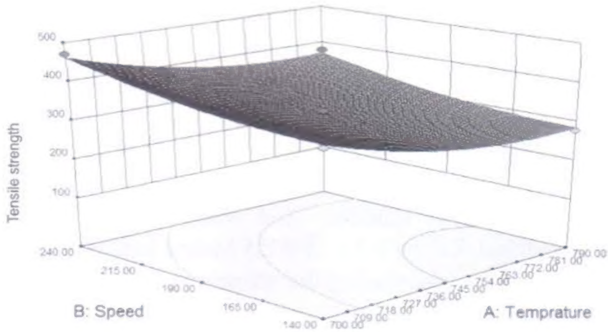

Fig.14 3D graph between speed, temperature and tensile strength

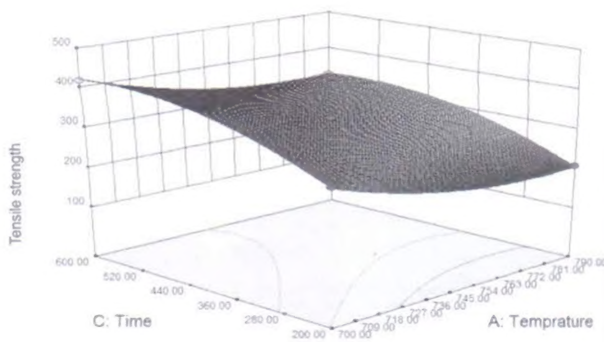

Fig .15 3D Graph between time, temperature and tensile strength

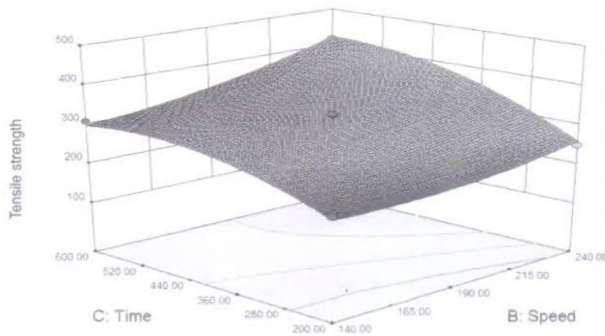

Fig. 16 3D Graph between time, speed and tensile strength

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